Life Cycle Management (Subject editor: Gerald Rebitzer)

Fundamental Principles for CAD-based Ecological Assessments *

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Abstract

Background, Aims, and Scope. As products are, directly and indirectly, main sources for ecological impact, the overall enhancement of products' ecological behaviour is an important contribution to the protection of the Earth's biosphere. This is especially important in a world where the major economical system is based on a constant rise in industrial production, consumption, and disposal of products. The true ecological performance of a product can only be determined by consideration of the impact arising from the entire lifecycle, and by including all known impacts into the assessments. The state of technology provides a standardized framework for such life cycle assessments (LCA) in the ISO 14040 series (see ISO 1997), and numerous databases and software tools are available to support the conduction of LCA. To integrate ecological indicators into decisions of everyday product development, as natural as it is the case today with finite items, design, and costs, indicators based on a consideration of the product's entire life have to be generated with little effort and in short time.

Methods. This article describes the fundamental principles of a technology designed to integrate lifecycle information into common 3-dimensional product models, like the ones used within modern Computer Aided Design (CAD) systems. Thereby, ecological assessments can be effectively undertaken during product development, where most of the environmental lock-in of a product is defined (see Lewis et al. 2001). Overall effects of alterations in materials or other product properties can be assessed instantly, supporting on the spot decisions to reach an improved product design.

Results. Next to an information model that manages the product and process representation, the research on which this article is based also deals with the calculation of resulting indicators, database access to ecological indicators, a graphical user interface, and a synchronisation tool for the CAD system Pro/Engineer[1]. The developed concepts have been implemented as a prototype software[2] and validated in different stages.

Conclusions. The concepts described in this article are a foundation for tools that integrate ecological assessments into everyday product development, on the basis of 3-dimensional CAD systems. Reuse of existing CAD data, an improved understanding of the assessment structure by product developers, and an automated calculation of resulting indicators are approaches to largely enhance the efficiency of product-related ecological assessments.

Keywords: Computer aided design (CAD); design for environment (DfE); life cycle assessment (LCA); product development; product models

1 Background, Aims, Demands, and Concepts

A large number of methods, databases, and software tools for the assessment of ecological impacts of technical systems are available and in use today[3]. Such tools allow the modelling of systems and their interactions with the environment. Ecological inventories for processes are usually taken from ecological databases and processed by impact assessment methods to expressive indicators. The methodological framework for such life cycle assessments is defined by the ISO 14040 series, which prescribes four steps: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO 1997). Such assessments are based on processes throughout the complete product lifecycle and a large number of damage categories. Ecological assessments are a powerful tool to enhance products' ecological behaviour, like recommended in (ISO 2000). The term Design for Environment (DfE) is commonly used for the optimization of ecological aspects during product development.

To digitally integrate such ecological assessments into an enterprise's product development process is the aim of the research described in this article. The foundation is an information model that conforms to commonly used product models of CAD systems[4] and at the same time contains information and functionality for the undertaking of ecological assessments.

The idea of integrating Life Cycle Assessments into CAD is not a new one; numerous research projects have addressed this topic (e.g. Roche 2001). However, none of the approaches known to the author is based on directly integrating Life Cycle Information and Assessments into an object oriented virtual product model, like used in CAD systems. This solution ensures the highest methodological and technical compatibility to modern product development, and addresses all issues stated below.

1.1 Deficiency in available tools

Although existing LCA software, like Sima Pro (from Pré Consultants, Netherlands), GaBi (from PE Europe, Germany), and EcoScan (from TNO, Netherlands), allows ecological assessments at a high level of detail, it lacks the ability to be smoothly integrated into modern product development. Each assessment requires manual remodelling of product data, and the manual assignment of ecological datasets.

* This article is based on the doctorate thesis of Sebastian Leibrecht (Leibrecht 2005).

[1] Pro/Engineer is a product of Parametrics Technology Corporation (www.ptc.com). For an introduction into Pro/Engineer see (Tickoo 2003).

[2] More information and a download of the software can be found at www.ecologicad.com.

[3] A comprehensive overview of available technology for ecological assessments can be found in (Lewis et al. 2001).

[4] For a comprehensive introduction into 3-dimensional CAD see (Anderl 2004) and (Fährer 1998).

Very basic principles of the utilised methodological approaches in existing solutions prevent, or at least restrict, the digital integration into existing infrastructures. Structural items like assemblies, parts, and features, which represent the frame of virtual product data, are not considered as they are used in CAD systems. Instead, materials and processes, that are at the most mere attributes in CAD systems, are used for the main system structure.

Next to the technological complications in reusing existing product data, the discrepancy in the used terminology and structural thinking results in a difficult understanding between involved parties, and a methodological inefficiency.

The following statements reflect the most important discrepancies between actual tools for ecological assessments and tools for product development (CAD) from the product developer's viewpoint:

- A material is not a physical instance, but a property of parts to specify the physical consistence.
- Neither is a material a process, but a parameter of any material-related processes, like material production, recycling, or land filling.
- An assembly is not a physical part, but a logical container, which aggregates and aligns subordinate assemblies and parts.
- Neither materials nor product components result in ecological damage, but only lifecycle processes, like material production and disposal, transport, or energy consumption.

It is not only for the sake of logical correctness, but also for sake of consistency with modern product development technology, that these rules are used in tools and communication. This is the first and most important step to an efficient integration of CAD and ecological assessments.

Another fact that complicates this integration is that product data, which could originate from CAD systems, is not isolated from process data and ecological data. This complicates the distinction of different sources, which is vital for an automated data synchronisation. For example, by combining the type of a used material, the mass of the part, and the definition of a material production process in the same entity, a synchronisation of the product related part of the information without loss of other information is very restricted.

Many current LCA tools also do not consider the definition of an individual lifecycle for each component, and the normalisation to a functional unit by the definition of an individual lifetime for each component. In addition, parametric coherences between product components are seldom used to automatically calculate dependent masses and volumes on demand, or to adjust process properties to the actual product state. The model consistency is thereby put at risk, and the information management complicated.

These and other disadvantages of current technology are a direct motivation for the research of the article at hand. They form the base for most of the requirements, which are introduced within the following sections.

1.2 Use of CAD product models

To efficiently integrate ecological assessments into product development, a CAD-like product structure must be the foundation of the utilised model. The following list shows the most important definitions for such a structure:

- A product structure consists of assemblies, parts, and features.
- Assemblies, parts, and features are components of the product.
- Assemblies consist of subordinate assemblies and parts.
- Parts consist of features and have an assigned material.
- Features can be specialised to specific kinds of features.
- Each component can be subordinate to only one other component to ensure a hierarchical tree structure rather than a network.
- All components have a defined mass, volume, and surface area.

Fig. 1 illustrates a typical representation of such a product model.

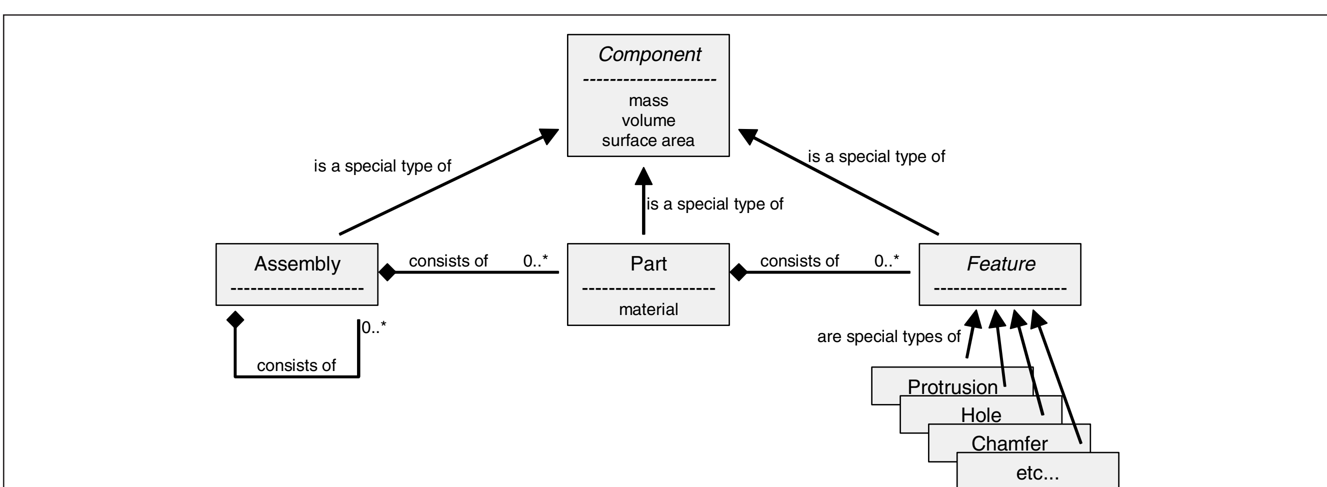

Fig. 1: Basic structure of product models

The notation is based on the Unified Modelling Language (UML[5]). Each box represents a class. A triangle (arrow) at a link means a generalisation between two classes, with the more general class at the triangle. All specialisations inherit their general class's characteristics. A rhombus at a link means an aggregation between two prospective objects, with the class of the knowing object at the rhombus. An aggregation can have different meanings, like consists of, owns, or has assigned, depending on the logical context. The multiplicity (0..*) defines that any number of objects can be involved on this side of the relation. A class name in italic defines an abstract class, which has to be specialised before instantiating objects. E.g. each component has to be an assembly, a part, or a feature. See also introduction into object-orientation at the beginning of section 2.

Most product models that are used within modern 3-dimensional CAD systems follow these rules, sometimes with small deflections[6]. An ecological assessment that is based on the same structural items could easily transform and reuse existing product representations directly from CAD systems.

1.3 Distinction between product and process data

A transformation or synchronisation of data from a CAD product model to a model used for ecological assessments requires a certain set of mapping rules. These rules relate entities and parameters of one model to another. To define such rules in a consistent way and without affecting unrelated information, similar items must be clearly identifiable in both models. This cannot be done if the assessment model does not distinguish between the static product representation, which can be mapped to a CAD model, and further information, like lifecycle processes. Therefore, the model must provide separate entities for product components and lifecycle processes, and store related information only in the affiliated items.

The following list relates the most important information to its affiliation:

Product components:

Structure of components (assemblies, parts, and features)
Physical properties (mass, volume, surface area, and material)

Lifecycle processes:

Structure of processes, type, and specialisation
Process parameters that are not affiliated to components

Only if information is stored in its logically affiliated entities, an automated management and synchronisation can effectively be implemented. To compute its ecological impact, for example, a transport process needs

- a specialisation (e.g. type of vehicle),
- the mass that is to be transported, and
- the travel distances for the actual transportation and additional travelling (e.g. the way back).

[5] See (OMG 2003) for the specification and (Fowler 2003) for a guide to the Unified Modelling Language.

[6] For a comprehensive introduction into product models see (Schichtel 2002).

The type of process (transport), its specialisation (e.g. truck), and the distance are clearly process-related parameters, since they have no logical affiliation to a component (e.g. an assembly). Therefore, they must be stored in the entity describing the process. The mass that is to be transported is clearly a parameter of the product itself, since it directly results from the product's geometry and material(s). Therefore, it must be stored in the entity describing the component (or can be calculated there on demand). To compute the ecological impact that results from this transport process, the required parameters have to be derived from the entities in which they are stored.

1.4 Definition of individual lifecycles and lifetimes for components

In most cases, each component of a product will have its unique lifecycle. Some processes and stages might be the same for a complete product, e.g. delivery or use processes. Other processes might occur only with a certain assembly, part, or feature, e.g. manufacturing processes. Therefore, the definition of processes on all structural layers of the product model must be possible. This can be realised by enabling the assignment of lifecycle processes in any amount to any component, whereas the processes on a higher hierarchical level also affect all subordinate components. To define a complete lifecycle, each component must have one or more processes of each lifecycle phase: production, use, and end-of-life, including transport processes. **Fig. 2** shows the linkage between product components and lifecycle processes. The process parameters depend on the specific type of process, and are therefore defined in the specialised process classes. The specialisation does not necessarily have to be done with specialised classes, as shown here, but could also be done by adjusting process objects (of the class Process) to the specific type.

In addition to the lifecycle, defined by processes, each component must define its own lifetime. An individual lifetime must be assigned to each component rather than to the complete product. This enables the consideration of replacement of components, the consumption of components, e.g. during use, and the reuse of components. The lifetime must be used to normalise assessment results to a functional unit.

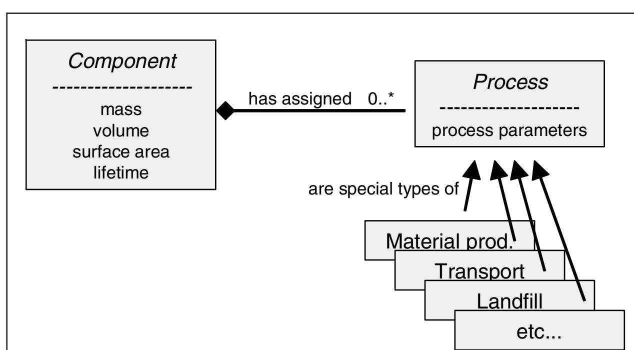

Fig. 2: Definition of lifecycles for product components. See Fig. 1 for the UML-Notation

1.5 Automatic prediction of repetitive lifecycle processes

A product structure can consist of a very large number of components, which results in a high effort to define all pertinent processes. Most of the processes are periodical for certain types of components. The delivery and production of materials for parts, manufacturing processes for features, and recycling and disposal scenarios for parts, are such regularly occurring processes. They could be predicted automatically. To enable a reasonable effective use for complex product structures, the assessment tool has to be capable to automatically predict such typical, reoccurring processes, and assign them to the appropriate product components. This functionality has to be adjustable, since different boundary conditions can lead to variations of repetitive processes.

It must also be possible to adjust process data manually, since exceptions can occur for certain components or processes. Some processes, transport and use processes in particular, can hardly be predicted automatically, and the user must be able to define such lifecycle scenarios manually.

1.6 On-demand assignment of ecological datasets

Most current assessment tools assign and store ecological datasets with the appropriate element of the product and process representation after the assignment. Such a static link complicates the automatic adjustment of the assessment to changes of the product state. If, for example, a process Production of steel is assigned to a part, including the relevant ecological data, the type of material becomes redundant, since it is stored not only within the product representation but also within the process definition.

This is a violation of the concept to store information where it logically belongs to, as outlined in section 1.3. A problem occurs if the material of the part is changed, e.g. within the CAD system: the process cannot automatically react to this change, since it is already specialised to the previously defined material. Instead, the process and ecological data would have to be deleted and replaced to consider the new material. The synchronisation would influence not only CAD-related product data, but also processes. The situation is complicated as normally various processes of the same part are affected, e.g. material production, recycling, and landfill.

To prevent these complications and to be consistent with CAD product models, the material has to be stored together with the part, and not with the process. During assessment, material-related processes have to request the type of material from the part, and then determine the appropriate ecological data. Thereby, a change in the product representation (e.g. the material) does not influence the definition of the lifecycle processes. During assessment, the processes calculate the resulting ecological impact on basis of the actual state of the product model.

These principles are valid not only for parts and materials, but for all types of product components and their parameters, as mass and volume.

1.7 Utilisation of parametric coherences

The diffusion of static product data with lifecycle information complicates the utilisation of parametric coherences within the product representation. Volume and mass of product components have some physical dependencies, which can help with the automatic control of their values within a product model. Such an approach ensures the consistency of these parameters and save the effort to manually calculate and define their values.

The first dependency is the addition of the total mass or volume of a product component by its subordinate components, as shown in **Eq. (1)** and **Eq. (2)**. The amount of subordinate components is stated by n.

$$mass_{component} = \sum_{k=1}^{n} mass_{subordinate\,component\,k} \tag{1}$$

$$volume_{component} = \sum_{k=1}^{n} volume_{subordinate\,component\,k} \tag{2}$$

Applied to the tree-like product structure, these equations result in iterative loops. If a mass or volume for an assembly is requested, the model can automatically calculate the value by adding together the appropriate values for the subordinate items, which, again, can be calculated in the same way. Thereby it is sufficient if actual values are stored for components at the end of the tree structure, e.g. for parts or features.

The second dependency is the physical coherence between mass, volume, and mass density of materials, as shown in equation **Eq. (3)**.

$$mass_{component} = volume_{component} \cdot density_{material} \tag{3}$$

This coherence can only be applied to features and parts, since they are the only components that are guaranteed to consist of a uniform material.

The product model can take advantage of these dependencies by enabling the automatic calculation of such values by the following scheme:

- The value for volume or mass for products, assemblies, and parts is calculated by adding together the appropriate values of the subordinate items.
- If the result is zero, the value is calculated by the coherence of mass, volume, and mass density (only for parts and features).

However, it must be possible to overwrite such automatic calculations if desired.

2 Framework for a Product and Process Model

The central part of any information-related technology is the structure in which the information is stored and managed – the information model. It is therefore the basic part within the development of any such systems to design a suitable model.

In modern software development technology, object-oriented approaches have widely replaced process-oriented approaches. Object-oriented software consists of a number of objects, which solve problems by communicating with other objects. Each object has a certain task, and stores the associative pieces of information in its attributes. The values of an object's attribute define the state of the object. Next to the storage of these values, objects provide functionality to access, manage, and process this information in their methods. The attributes, methods, and relations to further objects of an object are defined in the object's class, which has to be stated to create any object. While objects define a dynamic runtime structure, the static class structure is actually implemented in a programming language. Therefore, the design of classes and class models are the main foundation of object-oriented models.

In this section, an appropriate object oriented product and process model is designed, based on the requirements and concepts presented in section 1.

2.1 Class model

To be compatible with 3-dimensional CAD systems, the product and process model behind assessment tools must harmonise with the model structure of CAD systems, as elaborated in section 1.2. Since such a static product description is not sufficient for ecological assessments, a lifecycle definition based on processes, as derived in section 1.4, has to be added to the model. **Fig. 3** shows the class model resulting from the combination of the class models in Fig. 1 and Fig. 2. Although variations of the structure might be possible, this simplified model is an essential rough framework for tools that efficiently integrate ecological assessments and product representations of 3-dimensional CAD systems.

The model implements the following basic structural rules:

Generalisations:

- Assemblies, parts, and features are special types of components.
- Protrusions, holes, chamfers, etc. are special types of features.
- Material production, transport, landfill, etc. are special types of processes.

Aggregations:

- Assemblies consist of any number of further subordinate assemblies and any number of parts.
- Parts consist of any number of features.
- Each component can have any number of processes assigned.

Information management:

- Each component has a mass, a volume, a surface area, and a lifetime.
- Each part has one material (otherwise it must be an assembly, or the material is a composite).
- Each process has parameters, dependent on the type of process.

This model is suitable to reuse existing CAD product data mainly by

- providing appropriate classes for items that occur in CAD models,
- thus enabling an easy mapping of information,
- separating items for product data (components) and lifecycle data (processes), and
- enabling the definition of an individual lifecycle and lifetime for each component.

Further demands and functionality that were derived in section 1 can be integrated into the model by means of appropriate methods for the shown classes.

2.2 Application of the model

The purpose of a class model is to instantiate a runtime system of objects. The objects contain the information and functionality defined in their classes, and can have links to other objects appropriate to the aggregations defined in the class model. If each component is subordinate to only one other component, as outlined in section 1.2, the instantiation of objects appropriate to Fig. 3 can only result in a tree-like structure of objects.

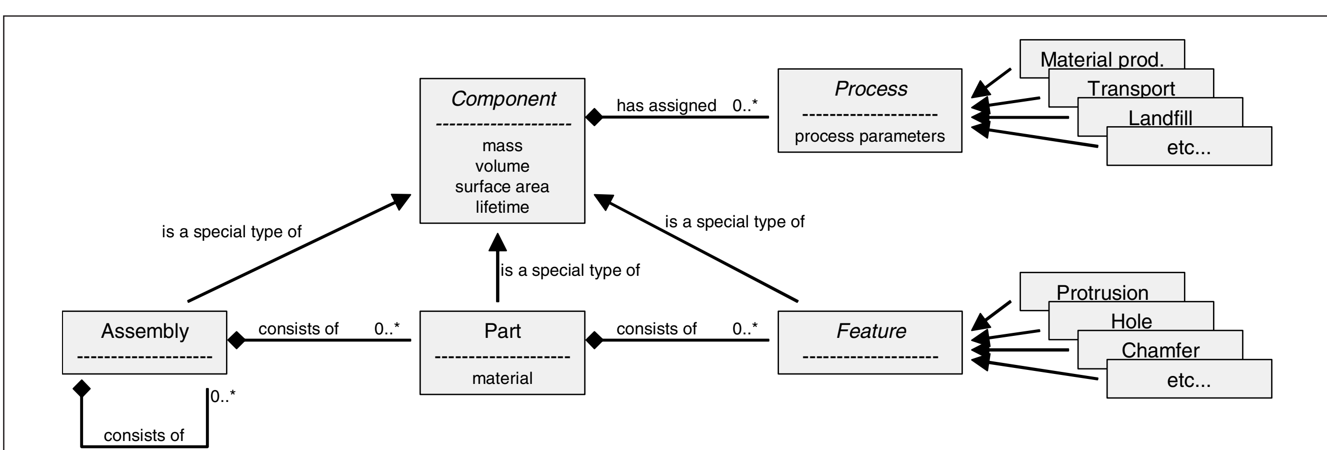

Fig. 3: Class model for product and process structure. See Fig. 1 for the UML-Notation

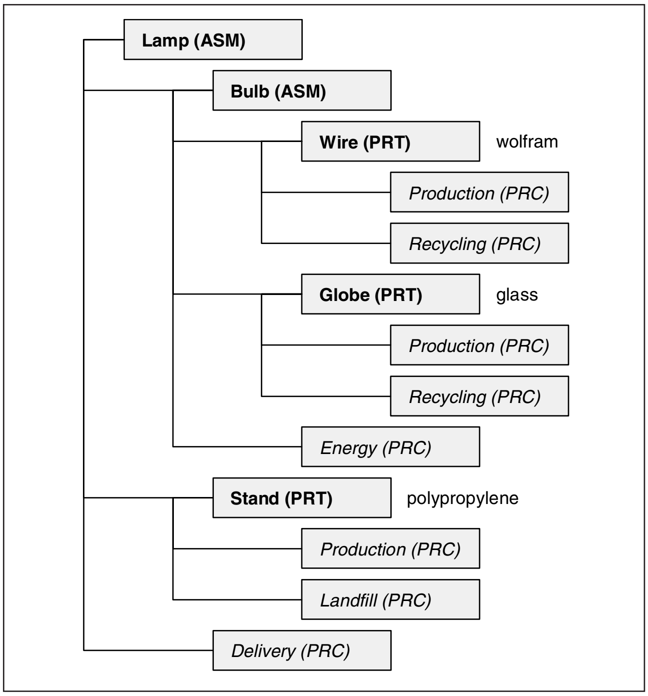

Fig. 4: Example of a product representation

The model in **Fig. 4** shows a very simplified representation of a lamp, consisting of the following objects:

- An assembly lamp, which contains a subordinate assembly bulb, the part stand, and a process delivery.
- An assembly bulb, which contains the parts wire and globe, and a process energy *(consumption during use)*.
- A part wire, made of wolfram, which has processes production and recycling assigned.
- A part globe, made of glass, which has processes production and recycling assigned.
- A part stand, made of polypropylene, which has processes production and landfill assigned.

This tree like product representation matches the structure used in CAD systems, and additionally defines lifecycle processes. For the sake of simplicity, features are not included in this example, and attribute values (except for the material) are not shown. Only the processes result in direct ecological impact. To determine the ecological impact for the wire's production process, the mass and type of material would have to be derived from the component (the wire), the type of process and possible process specialisations from the process.

The undertaking of ecological assessments, based on such a product representation, requires a suitable methodology to compute the ecological impact for any item.

3 Method for the Calculation of Ecological Indicators

Since ecological impact always originates in processes, ecological indicators always derive directly or indirectly from the processes of the product's life. Physical product components, like assemblies, parts, and features, define the structure in which the processes are arranged, and can hold information necessary for the calculation of ecological impact (e.g. mass, volume, or type of material).

Within this section, a method for the derivation and calculation of ecological indicators is developed. This is not to be confused with an impact assessment method, which computes expressive indicators from inventory data. The method developed here defines how to derive and update indicators for items of the product structure. Two cases can occur, which result in different methods. The first case is that the assessed item is a process. The second case is that the found item is a component.

The method presented here is universally applicable for the calculation of inventories – e.g. as a base for a full impact assessment – and for the derivation of pre-calculated equivalents or single scores – e.g. for an abridged assessment. The access to appropriate inventories and indicators is presumed.

3.1 Normalisation to functional units

Each assessment is based on a unique functional unit, which represents the service a product is meant to deliver. Examples for functional units are one km of driving (for a car) or the preparation of one cup of coffee (for a coffee maker). The result of an assessment states the ecological impact that results from the delivery of one functional unit. Although the functional unit is delivered in the use phase of a product, the results still consider the complete lifecycle of a product. To calculate the correct proportion for the functional unit, the result of each process has to be divided by the lifetime of the component that owns the process.

For example, the result for the CO_2 emission of one km driving with a car has to include the correct proportion of the CO_2 emissions that result from the production, delivery, use, and end of life processes of the car, since all these processes are vital to make the car drive the one km. If a gasket in the engine lasts for 120 km, the emissions of the production and disposal for this gasket have to be divided by 120 km to get the correct proportion for the functional unit of one km.

This approach can be used to consider components with different lifetimes and process aids, like coffee filters. If the functional unit for the assessment of a coffee maker is the preparation of one cup of coffee, the lifetime of a coffee filter might be 5 cups of coffee, while the lifetime of the coffee maker might be 4000 cups of coffee. The impacts for the production and disposal of both components are divided by the components' lifetimes, and are thereby normalised to the same functional unit. Thereby it is easy to compare and add the results.

3.2 Method for assessing lifecycle processes

Processes result in ecological impact, so indicators expressing and valuating this impact must be derived during ecological assessments. Such ecological data is not stored together with the process, but is allocated and adapted during the actual assessment, as outlined in section 1.6.

An ecological database is necessary to deliver impact information for processes with standard units, e.g. CO_2 emission

during the production of 1 kg of steel. A suitable indicator from the ecological database, dependent on the process type and, if needed, the used material, has to be derived for each process. The format and access to the ecological database is not discussed further, and is taken as granted.

The types of factors used to adapt the indicator to the actual process scenario also need to be determined, e.g. mass and distance for transport processes. The values of these factors are then requested from either the component or the process (dependent on the type of factor) and multiplied by the derived indicator value. Finally, the resulting indicator value is normalised to a functional unit by dividing it by the lifetime of the component.

Eq. (4) presents the calculation of an ecological indicator for a certain lifecycle process, where n is the amount of factors from the process and m is the amount of factors from the component.

$$indicator_{process} = \frac{indicator^{\#} \cdot \prod_{k=1}^{n} factor_{process_k} \cdot \prod_{l=1}^{m} factor_{component_l}}{lifetime_{component}} \tag{4}$$

The value for $indicator^{\#}$ is derived from the ecological database for the appropriate type and specialisation of process. It is valid for a standard unit, e.g. transportation (with a certain vehicle) of 1 kg for 1 km. The values for $factor_{process}$ are derived from the process itself, e.g. the travel distance. The values for $factor_{component}$ are derived from the component that owns the process, e.g. the mass of the component. The value for $lifetime_{component}$ is also derived from the component and used to normalise the result for this component to one functional unit. It must be stated in functional units, e.g. one km of driving or preparation of one cup of coffee.

3.3 Method for assessing product components

Although a component itself does not result in ecological impact, but only its processes, it can still be assessed to derive the impact that results from the components lifecycle. The result of such an assessment is the sum of the impact from all processes directly or indirectly (through sub-components) attached to this component. **Eq. (5)** shows the calculation of an ecological indicator for a component, where n is the amount of directly assigned processes, and m is the amount of subordinate components.

$$indicator_{component} = \sum_{k=1}^{n} indicator_{process_k} + \sum_{l=1}^{m} indicator_{subordinate\,component_l} \tag{5}$$

The values for $indicator_{process}$ are determined for all processes that are directly assigned to the assessed component by using the method developed in the previous section. The values for $indicator_{subordinate\ component}$ are derived for all direct subordinate components using the method developed here in an iterative call. Applied to the example in Fig. 4, the indicator for the lifecycle of the lamp is calculated by **Eq. (6)**.

$$\begin{aligned} indicator_{Lamp} &= indicator_{Bulb} + indicator_{Stand} + indicator_{Delivery(Lamp)} = \\ &indicator_{Wire} + indicator_{Globe} + indicator_{Energy(Bulb)} + \\ &indicator_{Production(Stand)} + indicator_{Landfill(Stand)} + indicator_{Delivery(Lamp)} = \\ &indicator_{Production(Wire)} + indicator_{Recycling(Wire)} + \\ &indicator_{Production(Globe)} + indicator_{Recycling(Globe)} + indicator_{Energy(Bulb)} + \\ &indicator_{Production(Stand)} + indicator_{Landfill(Stand)} + indicator_{Delivery(Lamp)} \end{aligned} \tag{6}$$

The iterative operation does not distinguish between subordinate components or processes, but just queries their assessment result, no matter what specific type they are. Depending on the type, either the same method (iteration for a subordinate component) or the method developed previously (for a subordinate process) is called. In the end, the total impact is tracked back to the lifecycle processes, of which each is treated by equation Eq. (4) . All these indicators must be of the same type and unit, e.g. Eco Indicator 99, Cumulated Energy Demand, or CO_2 emission.

4 Realisation, Validation, and Outlook

The concepts discussed here define basic principles and rules for integrating ecological assessments into product models like used in 3-dimensional CAD systems. There are various ways to realise appropriate software tools.

One approach is to directly extend the models and user interfaces of CAD systems. Thereby, ecological assessments could be undertaken on the basis of the same model, and no data transformation would be necessary. Such a solution would also avoid the switching to another system, and could therefore result in very short innovation cycles. The disadvantage of such solutions is the dependence from the corresponding CAD system. The tools are normally neither usable as stand-alone applications, nor in conjunction with other CAD systems. The concepts could also be implemented in an independent application, with its own user interface. Synchronisation tools for various CAD systems could be developed, to enable a universal integration.

An approach based on a modular, open architecture, based on a unique information model that conforms to the principles discussed here, has been implemented as a prototype. The used system architecture can be seen in **Fig. 5**.

The system architecture is based on a client-server concept, whereas the information model represents the server. The main part of the information model, the core model, manages relevant product and process data. The information model also includes the access to an ecological database[7] to

[7] The database used for the prototype currently contains 36 different types of indicators for more than 380 processes, taken from the Eco Indicator 95 and 99 manuals (see Goedkoop et al. 1996, 2000) and from the Global Emission Model for Integrated Systems (see GEMIS 2003).

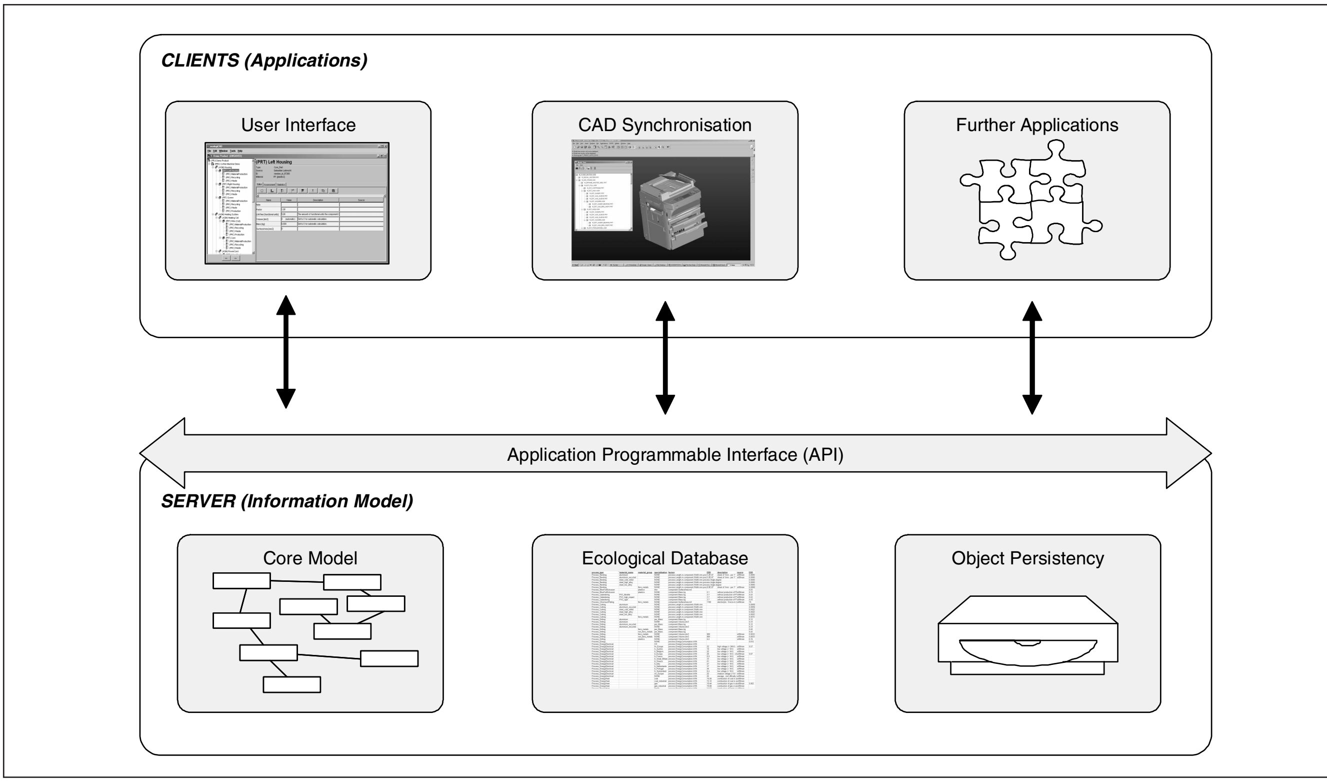

Fig. 5: Software architecture of total concept

derive indicators for lifecycle processes, appropriate to the method presented in section 3.2. Furthermore, a module for the persistent storage of modelled product and process scenarios is available (object persistency). The information model provides its functionality to further applications (clients) via an application programmable interface (API).

Two such clients have been developed to create a usable tool: a graphical user interface, which provides access to the information model's functionality, and a synchronisation tool for the CAD system Pro/Engineer. The API allows the creation or attachment of any further applications, e.g. other CAD systems or data formats.

The developed systems have been named ecologiCAD. The user interfaces can be seen in **Fig. 6**. In the background is the CAD system Pro/Engineer, with the additional ecologiCAD synchronisation menu. In the foreground is the assessment system, which has the product tree on the left side. The product tree shows the product's components and their structure, like assemblies, parts and features, plus the lifecycle processes of the components, which result in ecological impact. The main modes of the assessment system are an editor for the product structure and parameters, ecological assessments (by items, lifecycle phases, or different assessment methods), and statistical information (like number of items and bill of materials). Fig. 6 shows assessment results by items using the Eco-Indicator 99 method.

The complete system has been validated as a stand-alone assessment system and in conjunction with the CAD system Pro/Engineer. The results have been similar to those derived by existing LCA software, but are more dependent on the utilised ecological database than on the LCA software itself (see also Leibrecht 2005). Despite the restrictions of a prototype, the concepts proved accurate and applicable for effective ecological assessments during product development. Ecological hotspots and overall effects of product alterations could be identified with little effort. Next to the reuse of CAD data, the better understanding and recognition of the product representation by the product developer led to a more intuitive use of the assessment system. Nevertheless, the manual definition of certain product stages, e.g. use or transport scenarios, cannot be automated and still requires manual information input. A detailed analysis, development, and validation of the system can be found in (Leibrecht 2005). This publication also includes the system architecture and object oriented information models. The software can be downloaded at www.ecologicad.com.

A consequent development of the research into professional tools could integrate ecological indicators as a constant decision making factor into product development. For this an incentive for the application is vital. Such motivation originates much more in social and political aspects than in the availability of tools and methods, and life cycle assessments for consumer products are still little subject to political regulation. When such technology starts to be politically prescribed, like planned within the working paper of a prospective European Directive (see European Union 2003), the measurement of ecological lifecycle performance for products could become a widely used industrial tool.

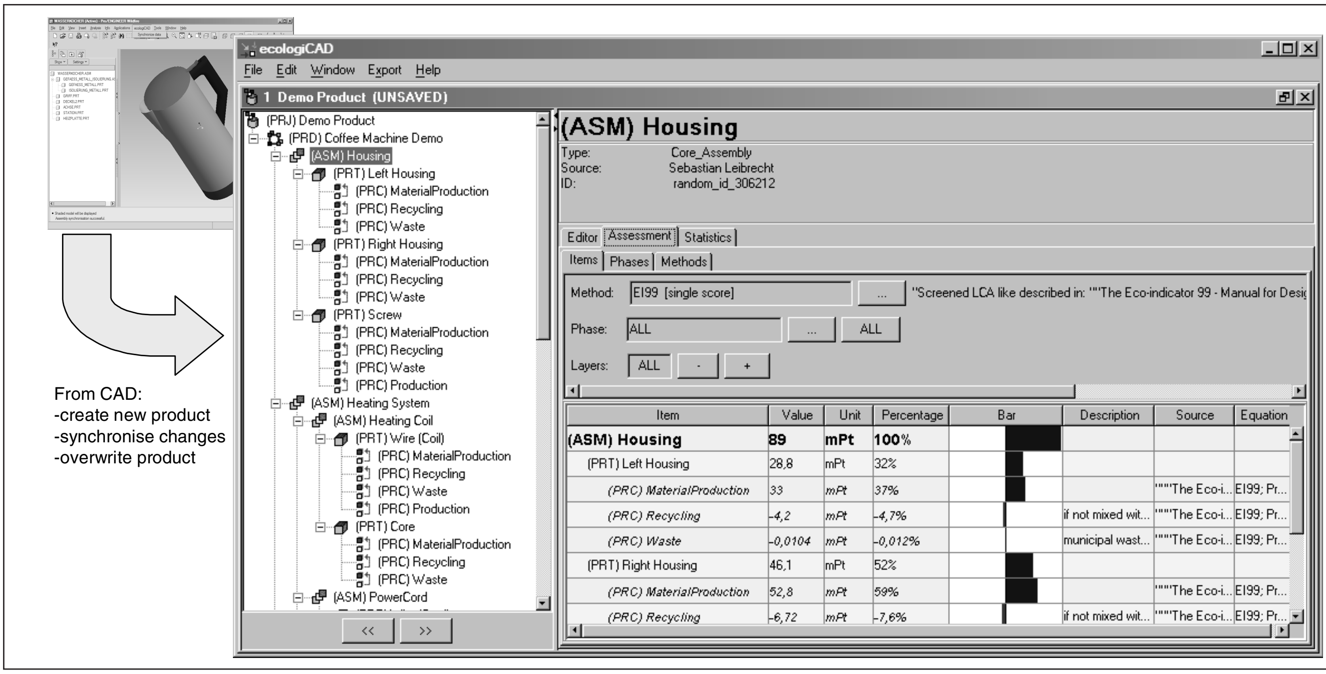

Fig. 6: Assessment results by product items in ecologiCAD, with Pro/Engineer in the background

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